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Current status of ground source heat pumps in Korea

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ABSTRACT

In Korea, ground source heat pumps (GSHP) have been gaining popularity for space heating and cooling. Because there are few sources of high-temperature geothermal energy in the country, public baths (25–40 °C) and geothermal heat pumps (~15 °C) using low-temperature groundwater or ground are the most dominant direct geothermal uses. The Promotion Law of the New and Renewable Energy Development, Use and Dissemination, enacted in 2004, imposed an obligatory installation of space heating and cooling systems using new and renewable energy sources including geothermal energy for newly constructed public buildings (more than 5% of total construction cost). Between 2004 and 2007, ground source heat pump systems occupied about 60% of the total public installation of new and renewable energy equipment. Starting with 35.2 kW of two facilities in 2000, systems with the capacity of over 127.1 MWt have been installed in 551 buildings (facilities) as of August 2008. The vertical closed heat pump system (closed loop) and the groundwater heat pump system (standing column well type; SCW) occupied 65.1% and 29.3%, respectively, among the total GSHP systems installed. The depth of the vertical loops ranged between 65 and 250 m (average 159 m) and the well depth of the SCW system ranged between 150 and 600 m (average 391 m). The number of geothermal energy companies, installing the GSHP systems, that are officially registered in the relevant authority increased from 5 in 2000 to 397 in July 2008. This paper presents details of the current status of ground source heat pumps in Korea.

Contents

1. Introduction

The Republic of Korea (ROK) is one of the top 10 largest oil-consuming countries in the world [1]. Furthermore, most of the domestic energy consumed (over 85%) in the country is derived from imports [2]. To keep pace with a world wide struggle to reduce CO_2 emissions and to cope with a rapid increase in oil prices, the Korean government has promoted the use of new and renewable energy (NRE hereafter) sources for various purposes, including residential heating and cooling. The Promotional Law of New and Renewable Energy Development, Use and Dissemination (revision of the 1987 Promotional Law of

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Alternative Energy Development) was enacted in 2004. The Law (article 12) and it is Enforcement Decree (article 15) enforced the obligatory installation of NRE systems for newly constructed and reconstructed public buildings and facilities. More than 5% of the total building constriction cost should be allocated for these systems.

Compared with many other countries such as Switzerland, Sweden, Canada, USA, and Iceland, Korea's use of NRE energy is still low [3]. The share of NRE sources in Korea's overall energy mix was 2.1% in 2004 [2]. The Korean government aims to raise this level to 5% in 2011 and 11% in 2030. To promote the use of NRE systems in public, commercial and residential buildings, the government subsidizes 30–80% of the total installation cost. Research and Development (R&D) funding for energy is relatively low (only 1.6% of the overall R&D budget), but the largest increase of funding has been found in the area of the new and renewable energy technologies, which has grown nearly fivefold during 2002–2006 [2].

In the meantime, following the enforcement of the obligatory installation of the NRE systems for public buildings and facilities in 2004, ground source heat pump systems are the first option for the public community. Over 60% of newly constructed public buildings during 2004–2007 adopted GSHP systems for space heating and cooling [4]. Because there are few sources of high-temperature geothermal energy in the country [5], utilization of ubiquitous shallow geothermal resources in de-centralized GSHP systems is an obvious option for space heating and cooling [6]. Until recently, small buildings have been the main targets for GSHP systems, but most recently the systems are being installed in very large residential and commercial buildings. Details of the GSHP systems in Korea are presented in this paper.

2. Climate and general geology

The Republic of Korea is located in the southern part of the Korean peninsular and covers 45% (99,601 km^2) of the total peninsular area (Fig. 1). Korea is surrounded by the South, East and Yellow Seas, including 3200 small and large islands. The climate ranges between continental and oceanic climates and it features four distinct seasons [7]. The hottest season is in August (average 23–27 °C) and the coldest is in January (average −6 to 7 °C). The annual mean air temperature ranges between 7 and 15 °C and it shows a gradual decrease with latitude (Fig. 2a). In high elevation areas (GW in Fig. 1b) the mean air temperatures are slightly lower by 3–5 °C compared with those of other surrounding areas. The annual mean groundwater temperature (measured at 70 m depth wells) ranges between 10 and 18 °C and it shows a negative correlation with topographical elevations (Fig. 2b) [8].

The geology of Korea is mainly comprised of granite, gneiss, schist, limestone and metamorphic rocks, which were mostly formed in the pre-Cambrian and the Paleozoic eras, while geological layers in the Cenozoic era are rare [7]. The pre-Cambrian metamorphic rocks are mostly distributed in northern and central parts of Korea and large Mesozoic strata are distributed in southern parts (GN, GB in Fig. 1b). Volcanic rocks in the Quaternary period are only present at Mt. Baekdu, Jeju Island and Ulleng-do [7]. There is no geothermal phenomenon such as very hot springs or high subsurface temperatures in these volcanic areas [5]. About 60% of the total surface of the peninsular is covered by granite and gneiss, except for lava flow areas including Mt. Halla, Jeju Island, Ulleung-do and Dok-do [7]. There have been no volcanic eruptions in the country since the last eruption of 25 thousands years ago at Jeju Island.

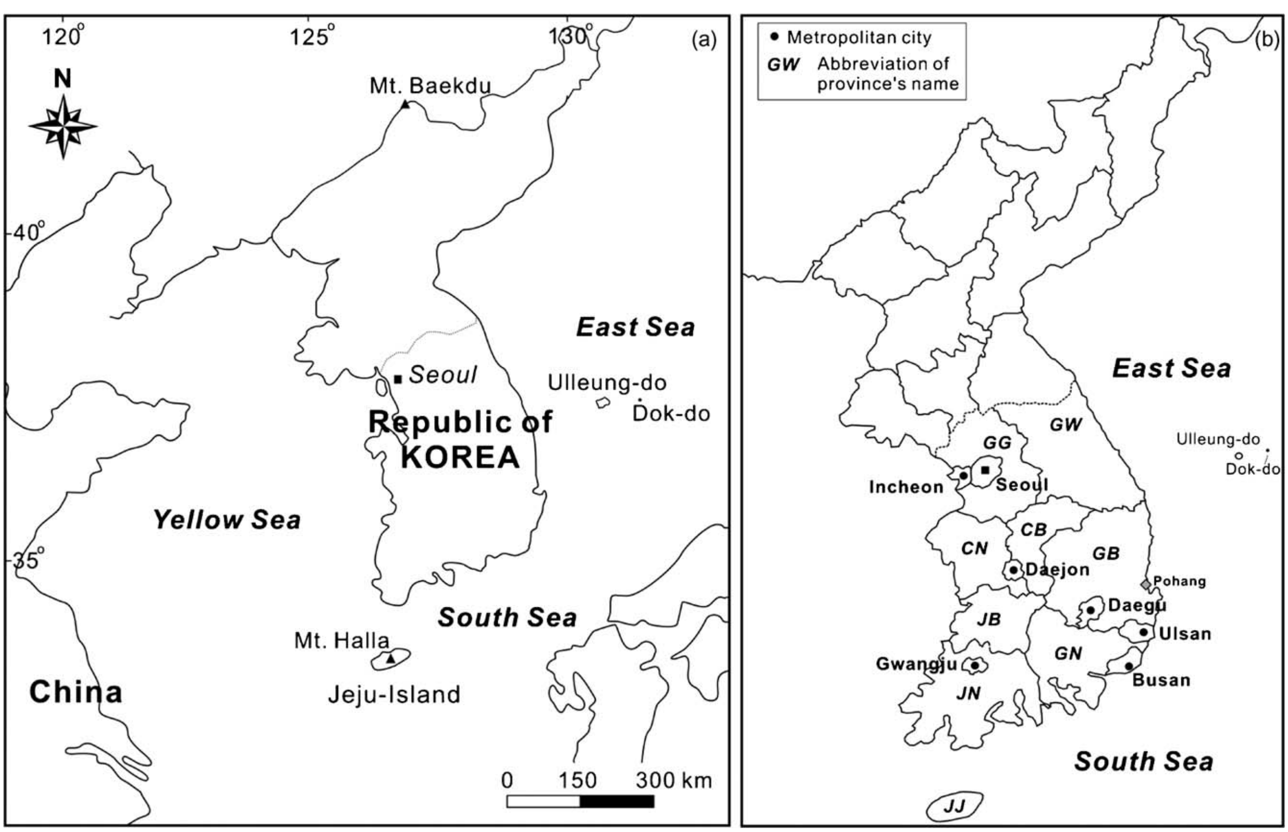

Fig. 1. Locations of (a) the Republic of Korea and (b) administrative local provinces [7].

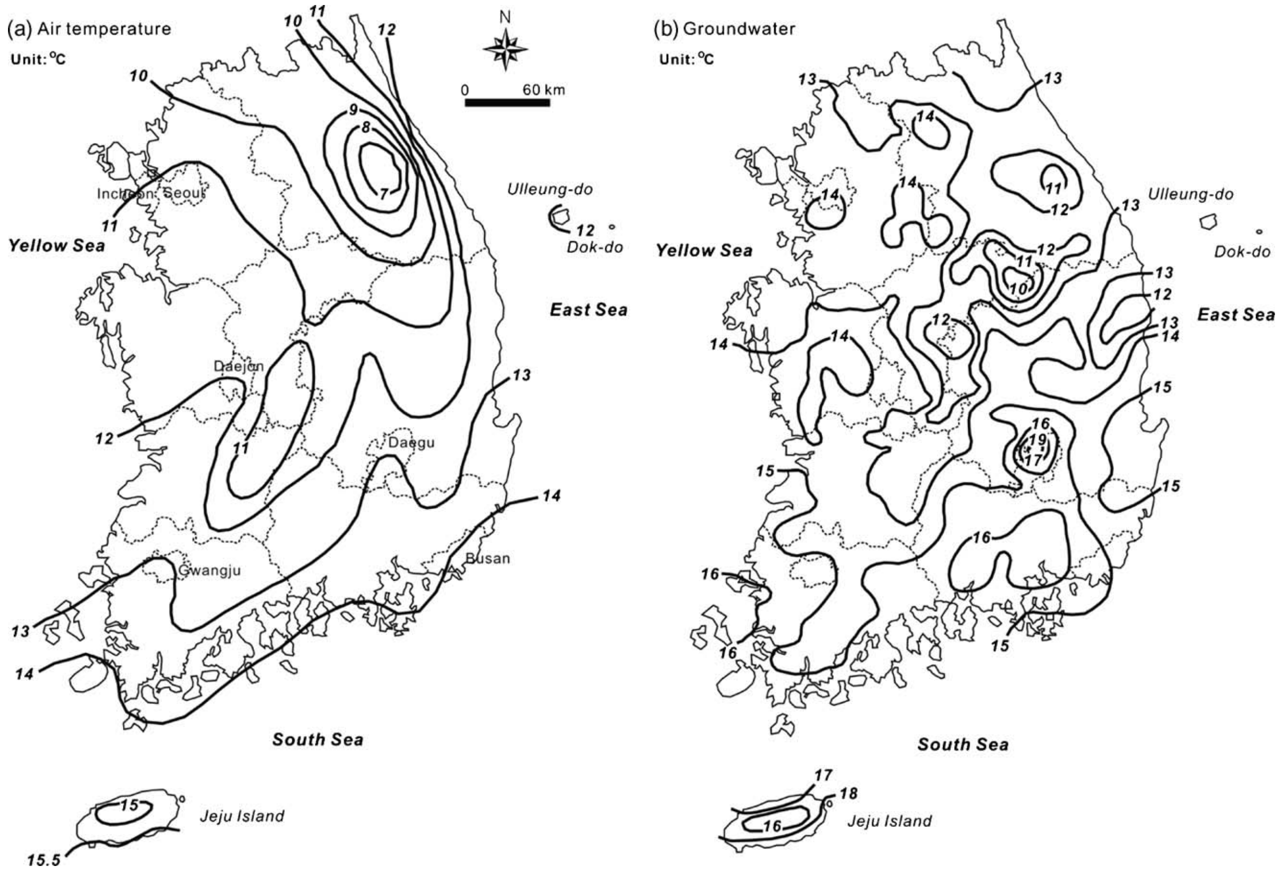

Fig. 2. Geographical distribution of (a) mean air temperature and (b) mean groundwater temperature of 70 m depth wells [8].

3. Direct use of geothermal energy

Before 2000, bathing and swimming were unique forms of the direct use of geothermal energy in Korea [5]. There are a significant number of hot springs (233 geothermal wells and 452 hot spring facilities), especially in areas of granite (formed in Jurassic and Cretaceous periods), some of which can be traced to more than 1000 yr ago [5,9]. The hot springs (water temperatures of 25–75 °C) are mainly distributed in the provinces of CN, CB and GN (see locations in Fig. 1b) [10], which coincide with the locations of relatively high subsurface temperatures (38–48 °C) at 1 km depth [11]. As indicated above, the relatively hot springs are not related to the volcanic activity but to the occurrence of granite. In December 2006, the direct use of geothermal energy in Korea was 260.63 TJ/yr and 62.65% of the total annual use is for bathing and swimming in public spa areas [3]. The direct use of geothermal energy has dramatically increased from 5.12 TJ/yr in 2002 by an annual mean increasing rate of 167%.

However, the development of low-temperature geothermal water for public recreational bathing and swimming has slightly declined since 2004 due to the increase of drilling cost and relevant environmental concerns [12]. Contrary to the declining or sustained trend of the balneological use, the use of ground source heat pumps has rapidly increased in Korea in public and commercial applications. There were only two buildings in 2000 where a GSHP was installed and their total system capacities were only 35.2 kW. In August 2008, the GSHP system capacities reached over 127.1 MWt and they were installed in 551 buildings (discussed below in detail), implying an annual mean increasing rate of 214% for 2000–2007 period (with respect to system capacity).

The first large-scale geothermal exploration and investigation for district heating (~75 °C) and greenhouse uses (~45 °C) was undertaken by the Korea Institute of Geoscience and Mineral Resources (KIGAM) in 2003 [5]. In this investigation, a few deep exploration wells were completed to depths of about 1000 m in Pohang city (located in GB province; see Fig. 1b). Based on results of these investigations, deeper geothermal wells will be drilled to a depth of more than 2000 m, from which 2000 tons of geothermal water will be pumped per day for heating 1500 nearby homes. In the meantime, while geothermal energy has not yet been yet utilized for electrical power generation [5], a plan for constructing a geothermal power plant at Jeju Island was announced in April 2008.

4. Ground source heat pumps

4.1. Installation of GSHPs

Since 2004, ground source heat pumps have been seriously considered as one of the alternative heating and cooling systems. Starting with only 2 buildings in 2000, GSHP systems have been installed for 551 buildings and facilities for space heating and cooling as of August 2008 (among them, installation years of 99 cases are unknown). Initially, while GSHPs were mostly installed in public buildings, they were not installed in private (residential houses) or commercial buildings. With the increase of financial support from government, the adoption of the GSHP has markedly elevated (Fig. 3a). Proportions of 5.9% in 2003, 26.2% in 2005 and 43.7% in 2007 of the total GSHP installations received governmental financial support (30–80% of total installation cost).

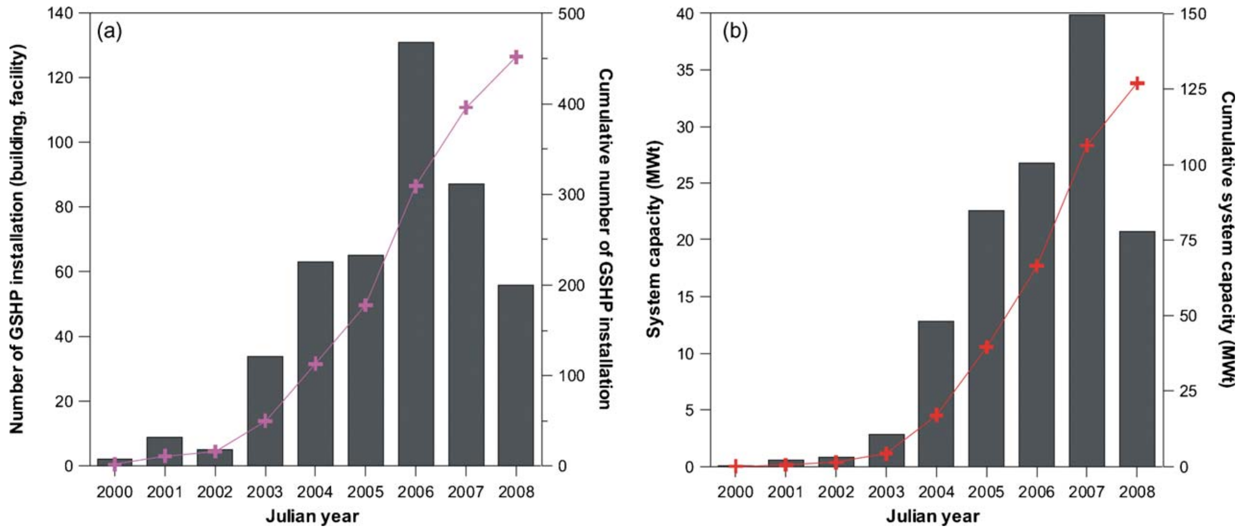

Fig. 3. Applications of GSHP systems in Korea. (a) number of GSHP installation for 2000–August 2008 (years of 99 cases are unknown) and (b) system capacity (191 cases are capacity unknown).

Correspondingly, system capacities (cumulative) markedly increased from 35.2 kW (0.035 MWt) in 2000 to 127.1 MWt in August 2008 (This figure is the minimum value because 191 cases among a total of 551 cases are unknown for system capacity) (Fig. 3b). Considering the average installed capacity of GSHP systems, the total system capacity would be about 200 MWt. In the meantime, an official report underestimated the installed system capacity and energy use of GSHPs (53.06 MWt and 264.5 TJ/yr as of December 2006) [3]. The statistics show minimum values because there is no obligation to produce an installation report to the governmental authority if the installations are not supported by the government and because they therefore did not include most of the installations in the private sector.

As indicated above, GSHP systems were installed mainly in public facilities including central and local government buildings and relevant authorities such as police stations and fire stations (30.1%). Educational (schools and universities; 12.5%) and social welfare buildings (olds and orphans care centers; 13.1%) also occupy large proportions (Fig. 4a). Applications for GSHPs for the commercial sector largely increased from 5.2% in 2006 to 29.0% in August 2008. Most of the commercial applications have occurred in recent years (2007–2008). However, the use of GSHPs is still low for private residential purposes. Fig. 4b shows the installed capacity of each GSHP system. Small capacity systems (<175 kW = 50 usRT) occupy the largest proportion (39.2%), which means that the GSHPs have either been used in an auxiliary capacity for main HVAC systems or they have been applied only for some parts of the entire building. Larger capacity systems (>703 kW = 200 usRT) were partly applied for university buildings with the help of open loop systems using groundwater. Most recently, applications of large GSHP systems have been attempted in newly constructed apartment buildings by a number of major construction companies [13].

Fig. 5 shows local distributions of the installed GSHPs. The majority of the GSHPs (43.1%) were installed in three provinces (GW, GG, Seoul in Fig. 1b), which are the coldest areas in the country due to relatively high latitudes. The lowest number of installations was found in two provinces (Ulsan and JJ), which are relatively warm areas. The annual mean air temperature of the latter two areas is higher by about 5 °C compared with that of the former three provinces. This fact indicates that the GSHPs are being operated mainly in heating mode [4].

4.2. Types of GSHPs

The GSHP system mainly comprises a heat pump and a system for exchanging heat with the ground [14]. The heat exchanging system

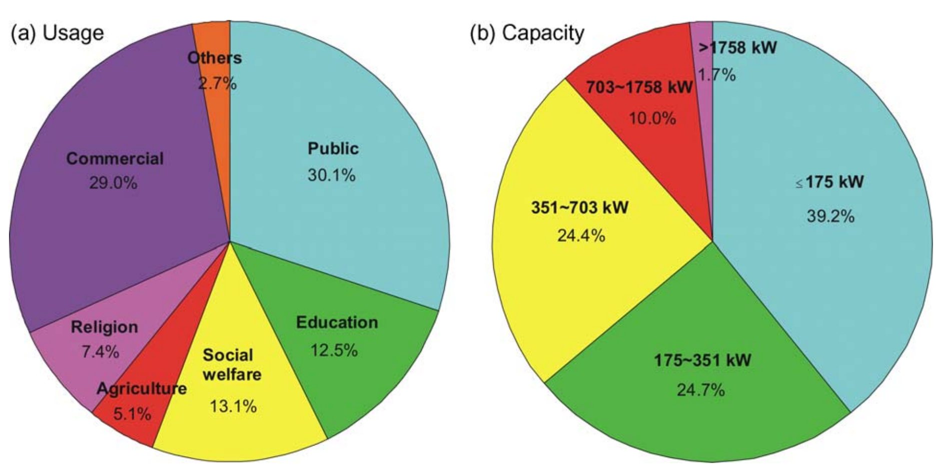

Fig. 4. Distribution of (a) usage and (b) system capacity of GSHPs. The usage is known for all 551 installations but system capacity is known for 360 cases.

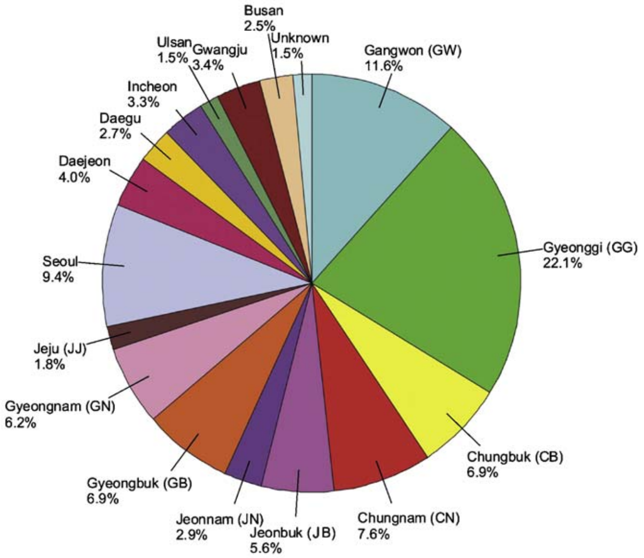

Fig. 5. Local distribution of the installed GSHPs (8 installations are unknown for locality).

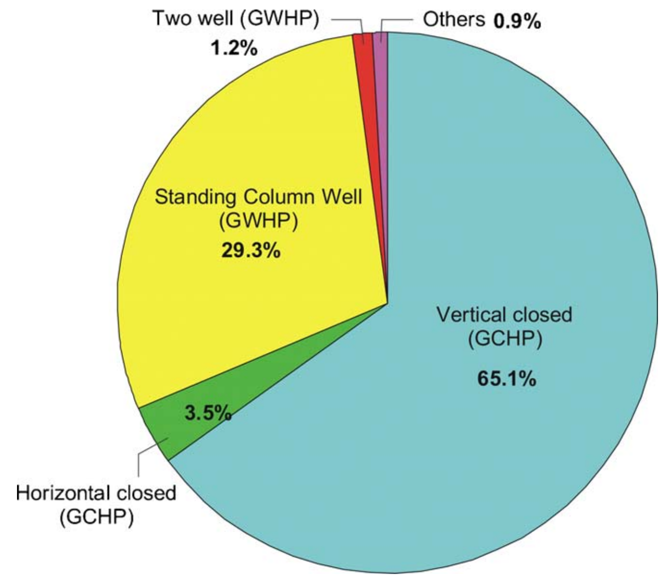

Fig. 6. Types of GSHPs installed in Korea for 2000–August 2008 (types of 210 cases among 551 installations are unknown).

can be configured as either a closed (ground coupled heat pump: GCHP) or open loop (groundwater heat pump: GWHP) and the loop itself can be either vertical or horizontal [15]. The open loop system typically uses groundwater as a heat carrier. The pumped groundwater can be either discharged onto the surface or returned into an aquifer after exchanging of heat. Groundwater heat pump systems in a semi-open loop arrangement are commonly known as standing column well (SCW) systems [16]. In the United States, 46% of GSHP installations are vertical closed loop systems, 38% are horizontal closed loop systems and 15% are open loop systems [17]. Similarly, in Germany about 15% of the GSHPs are open systems and 85% are ground coupled systems [18]. In Switzerland, groundwater heat pumps are relatively more used (30%) and horizontal and vertical closed systems occupy 5% and 65% of all GSHPs, respectively [17].

Fig. 6 shows the types of GSHPs installed in Korea from 2000 to August 2008. Among the known 341 installations for GSHP types, the closed loop system (GCHP) and the open loop system (GWHP) occupy 68.6% and 30.5% respectively, of all GSHPs. More specifically, vertical closed systems (65.1%) were predominantly installed and standing column wells (29.3%) have recently received much more attention in Korea mainly because the re-injection of pumped groundwater mitigated concerns of groundwater overdraft in conventional GWHPs and because there generally is competent rock below a few meters of subsurface soils [16]. Two wells open loop systems and horizontal closed loop systems have only small proportions.

In the vertical closed systems, several borehole heat exchangers are typically installed at depths of 20–100 m with a spacing of about 5 m [15]. The number and depth of BHE are dependent on various factors such as system capacity and thermal properties of geological formations [19]. Also in the SCW systems, deer groundwater wells are generally installed at the productive aquifer. In Korea, the depth of BHE ranged from 65 to 250 m and most of the BHE (82.9%) have depths of 120–200 m with an arithmetic mean of 159 m (Table 1). Considering the geological conditions of Korea (only a few meters of uppermost soil plus competent or slightly weathered rocks) [7], a large proportion of the full length of BHE would be installed at igneous or sedimentary rocks. In the SCW system, most of the groundwater wells (74.2%) were installed at depths of 300–500 m with a mean of 391 m. It is known that well depths of SCW systems in the United States are averagely 158 m for residential applications and averagely 377 m for commercial applications [16]. It is considered that deeper wells in Korea are necessary due to the installation of SCW systems in public and education buildings that have larger system capacities.

In general, the number of BHEs and wells is mainly dependent on system capacity. Thus, a larger system capacity requires a greater number of BHEs and wells. For most of vertical closed loop systems (40.6%), 10–30 boreholes have been adopted for exchanging heat with the ground and for 12.5% more than 70 holes for BHE have been installed (Fig. 7a). On average, 32 BHEs were installed for each GSHP. In each borehole, U shaped high-density polyethylene

Table 1
Drilling depths of borehole heat exchangers (BHE) for GCHPs and well depths for SCW.

GSHP types	BHE/well depth (m)	Number of installations	Mean depth (m)	Standard deviation (m)
Vertical closed	≤100	7	95	13
	101–120	3	117	6
	121–150	28	149	4
	151–200	30	182	17
	201–250	2	231	27
Subtotal	–	70	159	33
SCW	≤300	7	184	31
	301–400	10	384	22
	401–500	13	492	19
	>500	1	600	–
Subtotal	–	31	391	128

Relevant information was not available for 443 installations.

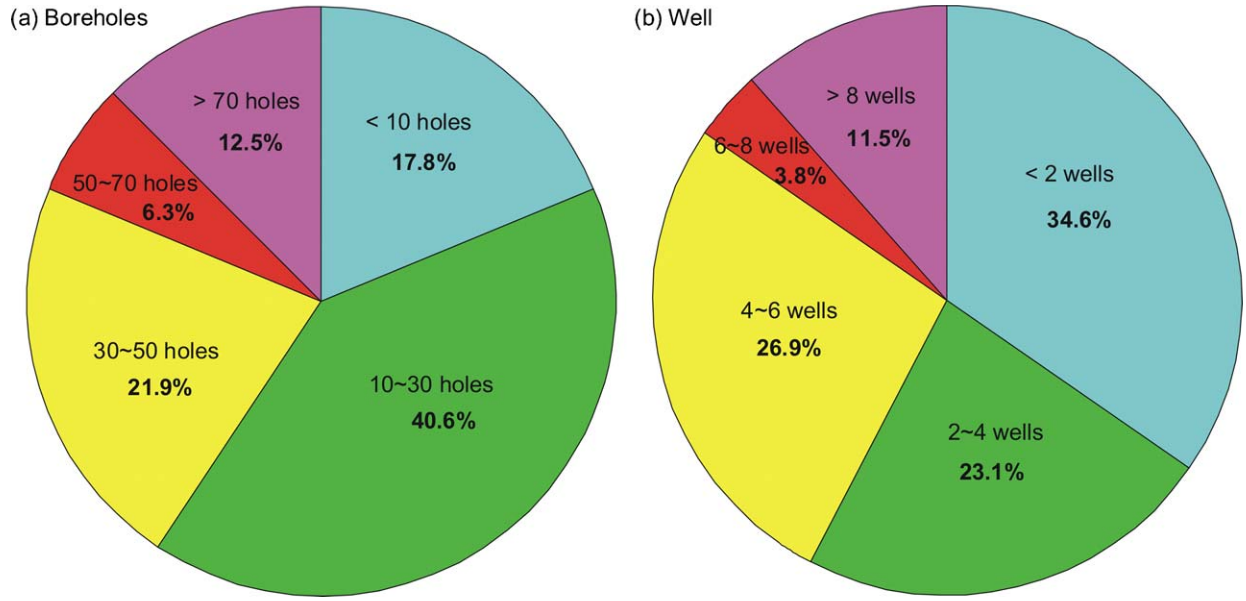

Fig. 7. Number of (a) boreholes (BHE) for vertical closed loop system and (b) groundwater wells for SCW system.

(HDPE) pipe was inserted. The borehole is usually filled with a mixture of Na-bentonite and silica sand to facilitate heat transfer from the heat exchanging fluid to the ground and to protect groundwater as required by relevant environmental regulations [20]. The SCW systems adopted various numbers of wells depending on system capacity (Fig. 7b). The number of groundwater wells ranged between 1 and 12 with a mean of 4.4 wells for each system. Similarly, with SCW systems in North America [16], well diameters were generally 150 mm in bedrock with 200 mm steel casing from the ground surface to the interface between upper soil and lower bedrock.

4.3. Installation costs

The installation cost of GSHP systems depends mainly on system capacity, type of GSHP and the degree of award competition in the market. Table 2 summaries installation costs of GSHPs. For the period of 2003–2006, the installation costs of only 68 cases are known. The minimum installation cost was $38,000 for closed loop system (35 kW) while the maximum cost was $1,164,000 for SCW system (1055 kW). With respect to the types of GSHPs, the total installation costs of SCW systems were higher than those of vertical closed loop systems mainly because of the larger capacity required for the SCW systems (Fig. 8a). However, this situation differs significantly with respect to cost per unit system capacity (1 usRT = 3.517 kW). The installation cost per unit capacity ranged from $2810 to $5030 with a mean of $4210 (Fig. 8b). In many cases (67.1%), the unit installation costs were between $4000 and $4800. With respect to GSHP types, the SCW systems are less expensive than vertical closed loop systems by an average of $190 per unit capacity (Table 3).

Meanwhile, the installation cost per unit capacity gradually decreased with years (an average of $4750 in 2003 to $4050 in 2006; Fig. 9). The decease in the cost appears to be derived from the progress of installation technology, the increased installation of less expensive SCW systems and award competition in the market between geothermal companies. Before 2007, the unit installation cost of vertical closed systems recommended by a relevant authority (Korea Energy Management Corporation) was $4550/usRT. In 2008, the authority revised the recommended unit costs to $4009/usRT for vertical closed loop systems and $3552/usRT for SCW systems, which applies for the government supported installations of GSHP systems [21]. Among the installation costs, the construction of BHE or groundwater wells occupies the largest proportion (25–40%) of the total cost [4,22].

4.4. Geothermal energy companies

There are many companies in Korea that specialize in the installation of GSHP systems. While there were only 5 geothermal companies in 2002, this number dramatically increased (especially from 2005) to 397 commercial companies as of July 2008 (Fig. 10a). Since 2005, every geothermal company in Korea is obliged to register with a governmental authority to engage in geothermal business. They should have a capital of more than $200,000, at least 2 nationally registered engineers and 1 technical expert related to the areas of machinery, electricity, architecture and civil engineering [4]. Among the 397 registered geothermal companies, 39% are

Table 2
Installation costs of GSHPs systems in Korea ($n = 68$).

GSHP types	Proportion	System capacity (kW)	Total installation cost ($)
Vertical closed	69.1%	306 ± 208[a]	370,590 ± 252,220
SCW	30.9%	503 ± 278	582,570 ± 311,270
Total	100%	366 ± 246	434,190 ± 286,200

Source: Ref. [3].
[a] Mean ± standard deviation.

Table 3
Unit installation costs of GSHPs systems in Korea ($n = 68$).

GSHP types	Proportion	Unit cost ($/usRT)	Maximum/minimum unit cost ($/usRT)
Vertical closed	69.1%	4260 ± 420[a]	3200/5030
SCW	30.9%	4070 ± 460	2810/4640
Total	100%	4210 ± 430	2810/5030

Source: Ref. [3].
[a] Mean ± standard deviation.

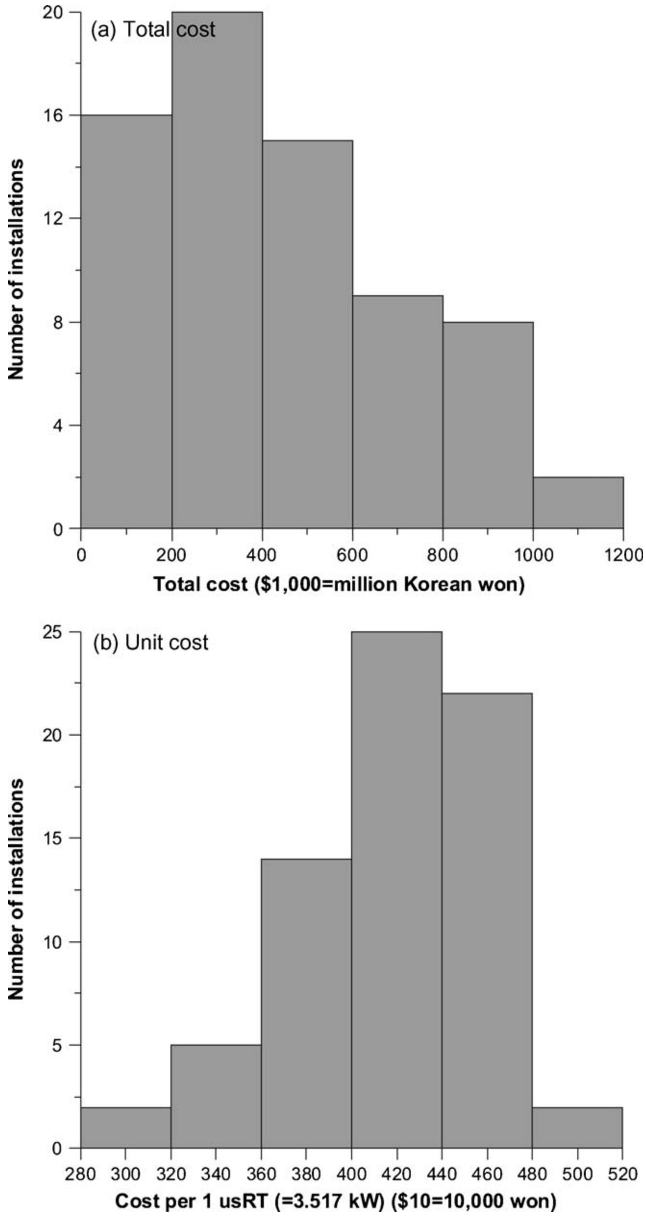

Fig. 8. Distribution of (a) total installation costs and (b) unit (per 1 usRT) installation cost.

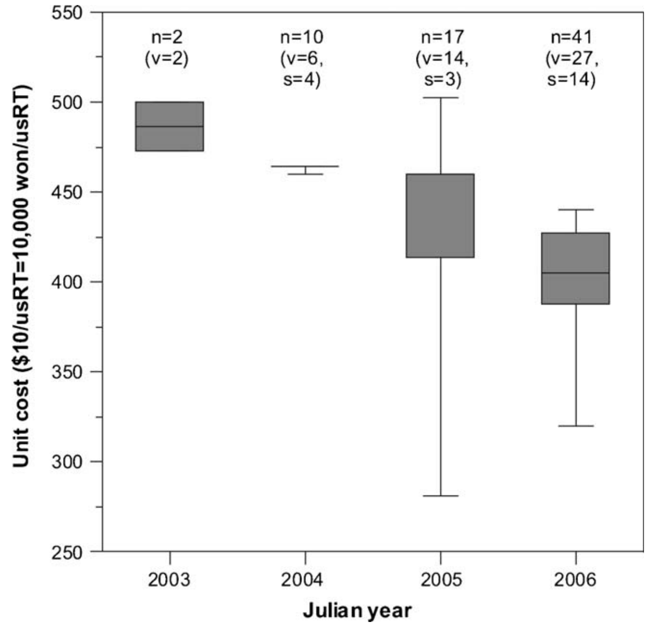

Fig. 9. Change in unit installation cost of GSHPs for 2003–2006. v, vertical closed loop; s, standing column well system.

located in three provinces (Seoul, GW, GG; see Fig. 1b), which are the uppermost areas of the country (relatively cold areas). Most of the geothermal companies (95.5%) have two or more business areas of new and renewable energies including solar energy, hydropower, and wind energy. There are a total of 2179 companies specializing in new and renewable energies as of July 2008. Among them, the companies specializing in solar energy have the largest proportion (61.2%) and the geothermal companies (12.5%) occupy the second largest (Fig. 10). The increasing number of geothermal companies showed a mean annual increasing rate of 236% during 2005–2007.

5. Regulations on GSHPs

Laws and regulations directly related to GSHPs include the "Promotion Law of New and Renewable Energy Development, Use and Dissemination (#8899)" and the "Groundwater Act (#9058)". The Promotion Law designates the geothermal energy as one of the new and renewable energies (article 2(1)) and imposes the obligatory installation of new and renewable energy equipment for newly constructed governmental and public buildings and facilities (article 12(2)). The Presidential Decree (article 15(1)) sets a minimum value of 5% of total construction cost that should be allocated for renewable energy equipment. In addition, in the decree (article 25(1)), requirements for registration are indicated for specialized renewable energy companies including geothermal companies.

The Minister (Ministry of Industries and Resources) Ordinance (#2008-3) entitled "Standards on Support, Installation and Management of New and Renewable Energy Equipments" gives details for the installation of the renewable energy systems that are financially supported by government. In the standards, standard procedures for GSHP systems are given including system location, design of heat source and BHE, specifications of heat pumps, ducts and pipes, and relevant environmental guidance. In order to obtain an official permit for installation of GSHPs and financial support, many documents such as topographic and geological maps of the system area, a summary of the system design, system calculations, detailed design sheets and results of a thermal response test (TRT), should be submitted to the relevant authority and reviewed by a geothermal committee.

Especially for open loop systems that include two wells and SCW systems, many environmental guidelines are indicated complying with the Groundwater Act to protect groundwater resources in aquifers [4]. The open loop systems using groundwater are also considered to be the same as conventional groundwater facilities in the Groundwater Act (article 7). Thus, a groundwater impact survey should be conducted prior to the system installation, which includes pumping and recovery tests (more than 48 h), analysis on the impact range in 5 yr, and groundwater quality analysis. The groundwater quality should meet standards for domestic use (Presidential Decree of the Groundwater Act, article 31).

The Groundwater Act has many articles related to the GSHP systems (Table 4). In the Act, five articles (articles 7, 8, 9(4), 9(5), 30(3)) are mainly concerned with the GSHP systems. The Presidential Decree (article 14(3)) of the Groundwater Act

Table 4
Regulations in the Groundwater Act related to GSHP systems [4].

Types	Regulations	Contents
GCHP	Act article 9(4), Decree article 14(3), Ordinance article 9(4)	Obligatory report on excavation affecting groundwater
GWHP (common)	Act article 7	Permit on development and utilization of groundwater, groundwater impact survey
	Act article 8	Report on development and utilization of groundwater, groundwater impact survey
	Act article 9(5)	Post management of facilities for development and utilization of groundwater
	Act article 30(3)	Imposition and collection of charges for using groundwater
	Ordinance article 5	Installation standards for groundwater development and utilization facilities
	Ordinance article 6	Request of permit on development and utilization of groundwater
	Ordinance article 8	Report on development and utilization of groundwater
	Ordinance article 9(5)	Management of facilities for development and utilization of groundwater
	Ordinance Table 2	Standard scheme of facilities for development and utilization of groundwater
	Ordinance form 2	Request form of permit on development and utilization of groundwater
	Ordinance form 7	Report form on development and utilization of groundwater
	Ordinance (ME) article 10	Targets for groundwater quality investigation
	Ordinance (ME) article 12	Frequency of groundwater quality survey (every three year for open loop systems)
SCW	Decree article 14(4)	Excluded from post management of facilities for development and utilization of groundwater
	Decree article 40(3)	Excluded from imposition and collection of charges for using groundwater

designates ground excavation (drilling) for installing BHE (for vertical closed loop) as an activity affecting groundwater environment and thus the driller (or owner) should report the excavation activity to local government with a document containing information of the drilling location, depth and drilling diameter. As stated above, in case of open loop systems including SCW, a groundwater impact survey should be conducted. All groundwater wells used for open loop systems should meet installation standards for conventional groundwater use facilities.

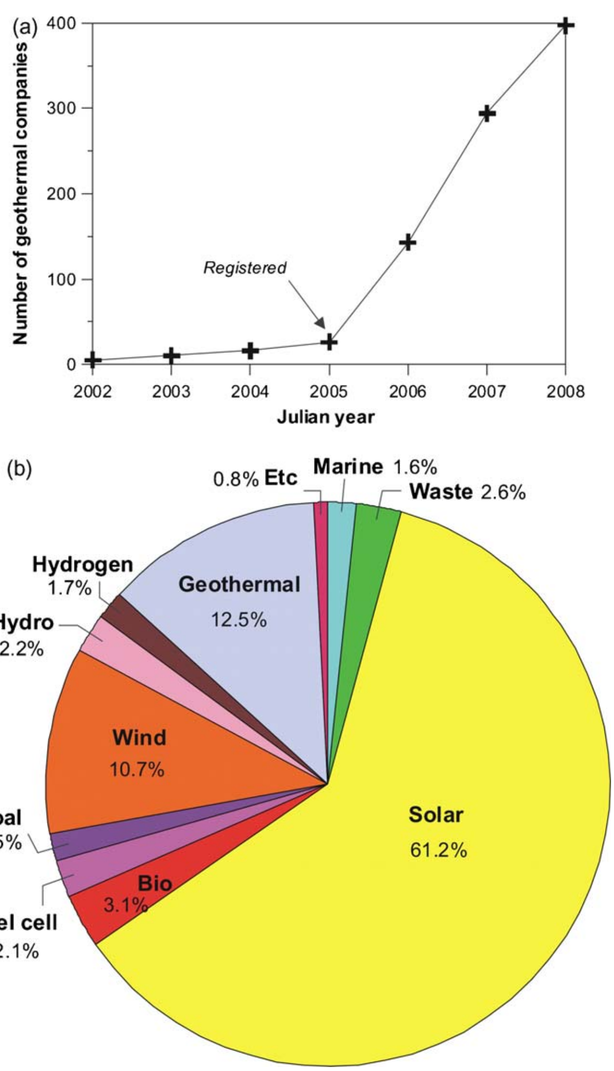

Fig. 10. (a) Number of specialized geothermal companies and (b) distribution of renewable energy companies [3].

Recently, in order to promote geothermal energy business and use of geothermal energy (GSHPs), in the amendments of Presidential Decree (#20877) revised in June 2008, the SCW systems were exempted from obligation to post management for the groundwater use facilities (Decree article 14(4)) and charges for groundwater use (Decree article 40(3)).

6. Conclusion

In this paper, the current status of GSHP systems in Korea was presented. In Korea, installations of GSHP systems are rapidly increasing in both private and public sectors. The GSHP systems are extremely energy efficient, clean and environmentally friendly. Recently, the Korean government announced that the share of renewable energy among the total energy use would be elevated to 11% in 2030 from 2.4% at present. In particular, dissemination of geothermal energy is scheduled to increase by 51 times that of the present figure by 2030. Despite this optimistic anticipation, there are a few barriers hindering the development and the use of geothermal energy, particularly for shallow low temperature energy. They include insufficient technical experiences (high cost of BHE installation), societal concerns of environmental aspects related to groundwater contamination and regulations not specifically tailored to the GSHP systems. All these problems can be tackled by the cooperative work of geothermal companies, researchers and regulation authorities. In the meantime, for more reliable statistics on geothermal energy use, the obligation to supply an installation report to the relevant authority should also be imposed on the private sector.

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References

[1] BP. BP statistical review of world energy June 2008. London: BP p.l.c.; 2008.

[2] IEA. Energy policies of IEA countries: the Republic of Korea 2006 review. Paris: IEA; 2006.
[3] KEMCO. New and renewable energy statistics 2006. Yongin, Korea: KEMCO; 2007.
[4] Lee JY, Kim CG, Lee JG, Kim JW. Interim report on effect of geothermal energy system on soil and groundwater environment. Gwacheon, Korea: Ministry of Environment; 2008 [in Korean].
[5] Song Y, Kim HC, Yum BW, Ahn E. Direct-use geothermal development in Korea: Country update 2000–2004. In: Proceedings of the world geothermal congress; 2005. p. 1–7.
[6] Sanner B, Karytsas C, Mendrinos D, Rybach L. Current status of ground source heat pumps and underground thermal energy storage in Europe. Geothermics 2003;32:579–88.
[7] Lee JY, Yi MJ, Yoo YK, Ahn KH, Kim GB, Won JH. A review of the national groundwater monitoring network in Korea. Hydrol Process 2007;21:907–19.
[8] Lee JY, Hahn JS. Characterization of groundwater temperature obtained from the Korean national groundwater monitoring stations: implications for heat pumps. J Hydrol 2006;329:514–26.
[9] Yum BW. Historical review of hot spring waters in the Republic of Korea. In: Stories from a heated Earth our, geothermal heritage; 1999. pp. 379–392.
[10] Hann SK. Mineral water and spas in Korea. Clin Dermatol 1996;14:633–5.
[11] Park SS, Yun ST, Chae GT, Hutcheon I, Koh YK, So CS, Choi HS. Temperature evaluation of the Bugok geothermal system, South Korea. Geothermics 2006;35:448–69.
[12] Yum BW. The present status of Korean geothermal research and investigations. In: Proceedings of the world geothermal congress; 2000. p. 499–504.
[13] HURI. A research for application of cooling-heating system using ground source heat in multi family apartment. Seongnam, Korea: KNHC; 2006 [in Korean].
[14] Seol Y, Lee KK. Application of TOUGHREACT to performance evaluations of geothermal heat pump systems. Geosci J 2007;11:83–91.
[15] Omer AM. Ground-source heat pumps systems and applications. Renew Sustain Energy Rev 2008;12:344–71.
[16] Orio CD, Johnson CN, Rees SJ, Chiasson A, Deng Z, Spitler JD. A survey of standing column well installations in North America. ASHRAE Trans 2005;3:109–21.
[17] Curtis R, Lund J, Sanner B, Rybach L, Hellström G. Ground source heat pumps-geothermal energy for anyone, anywhere: current worldwide activity. In: Proceedings of the world geothermal congress; 2005. p. 1–9.
[18] Schellschmidt R, Sanner B, Jung R, Schulz R. Geothermal energy use in Germany. In: Proceedings of European geothermal congress; 2007. p. 1–7.
[19] Kavanaugh SP. Field tests for ground thermal properties-methods and impact on ground-source heat pump design. ASHRAE Trans 2000;106:851–5.
[20] Bernier MA. Closed-loop ground-coupled heat pump systems 2006;9:12–9.
[21] KEMCO. Education materials for geothermal companies on 2008 general government supported dissemination projects. Yongin, Korea: KEMCO; 2008.
[22] Rafferty KD. Design issues in the commercial application of GSHP systems in the U.S.. GHC Bull 2000;3:6–10.